Dual Hydrogen-Jet Fuel Aircraft –A path to low carbon emissions

Energy and Mobility: Powering Mobility

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Underlined text is a hyperlink

1956 1st Dual Hydrogen-Jet Fuel Aircraft Demonstration

- B-57 switched existing engines to LH2 powered flight over Lake Erie
  - Liquid hydrogen was carried in a tank under the left wingtip of B-57 pressurized via gaseous helium tank under right wingtip
  - When engine was operating on H2, JP fuel was recirculated back to its tank. Taking off with jet fuel, hydrocarbon fuel in one engine was stopped and the flow of GH2 was initiated. A LH2 specially designed displacement pump located inside tank was added later.

First Hydrogen Fueled Aircraft Flight
Martin B-57 Canberra (1955)

Video circumstantially shows H2 Contrails have larger particles, hence shorter lifetimes to reduce climate forcing beyond GHG.

Requirement for **well-insulated, sealed, cryogenic tank and fuel system including infrastructure** represent challenges to the designer and **now require flight demonstrations** to raise technology readiness--
Start between two airports – Safety cannot be accessed without designs and hardware

Cryogenic systems and infrastructure do not pose an insurmountable problem for **dual hydrogen-jet fuel aircraft**--learn from the demonstrators, find the unknowns

42% of **Flight Segments are less than 2000km** which should **drive economical emission reduction strategy**
50% emission reduction in emissions if aircraft have 2080km of net-zero range

Outline

- 2020 European H2 Aviation Study
- 2021 U. S. Aviation Climate Action Plan and Status
- Dual Hydrogen Jet Fuel Concept
- Challenges of SAF - Sustainable (Alternative, Synthetic) Aviation Fuel
- New Aircraft Markets and Emissions by Range
- Dual LH2 Jet Fuel Vision to Lower Emissions – 60% less emissions
  – LH2 can provide ~ 2000 km of range for all ranges of aircraft
  – H_2 Hubs near pull locations acts as storage, powered by excess and affordable renewable energy, as microgrids, pipelines break bottlenecks
- Summary

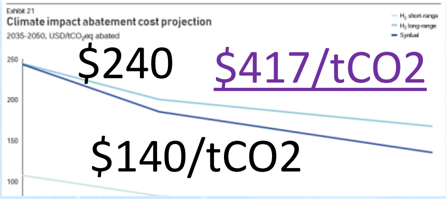
50% CO2 emission reductions if aircraft have 2080km of net zero range

2020 European Hydrogen Aviation Study

- "H_2 propulsion best suited for regional, short-med range", 20-30% PAX $ increase
- Long range remain Jet A; SAF is required
- 28 Petawatt-hrs (3200 GW)-2050 globally
  - ❑ Assumes 40% LH2
  - ❑ 2-3X energy SAFvsLH2

38 PWh 4300 GW-100% SAF
12 PWh 1450 GW-100% LH2

Ex 21: Assumes significant reductions in cost of carbon



LH2 reduces resources

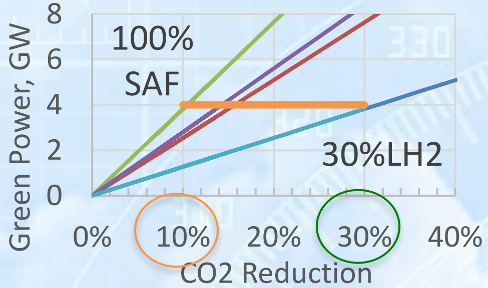
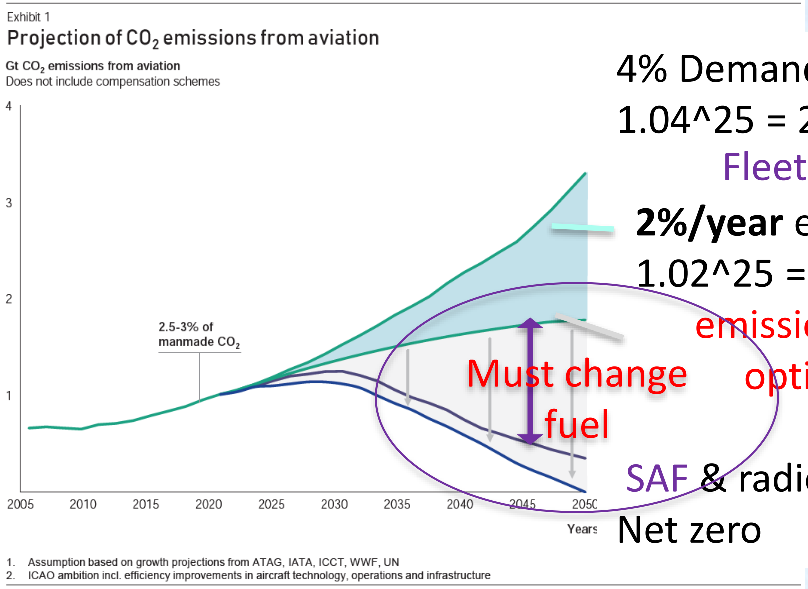


Exhibit 1 Projection of Emissions from Aviation



4% Demand Growth
1.04^25 = 2.7x
Fleet Improvements
2%/year eff improvements
1.02^25 = 1.6x
emissions double even with optimistic improvements
Must change fuel
1970-2019, 1%/yr
SAF & radical technology
Net zero

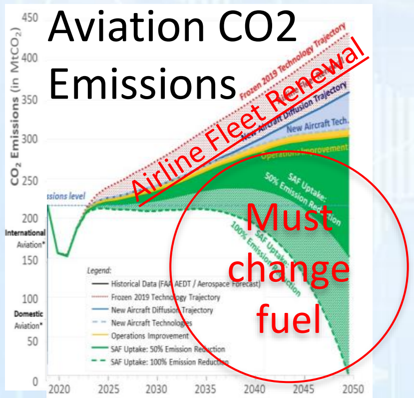
Pg16: "Main focus on decarborizing aviation should be on short-range aircraft flying less than 2,000 to 3,000 km, as well as on medium and long-range-range aircraft"

- **US Aviation Climate Plan View of the European Study:** "do not expect LH2 aircraft to make a significant contribution toward achieving net-zero emissions by 2050"

30 more years to lower emissions with Hydrogen

2021 U.S. Climate Aviation Action Plan

Achieve 2050 Net-Zero GHG mostly from Sustainable (Alternative) Aviation Fuel



- U.S. –> **Incentives**

$1.25/gal if 50% GHG reduction

$3/kg for green H_2 (20 years)

Goals: 3B gals-2030 30B-2050

- Europe->**Mandates**

ReFuelEU Mandate:

2% SAF 2025, 28% SAF 2050

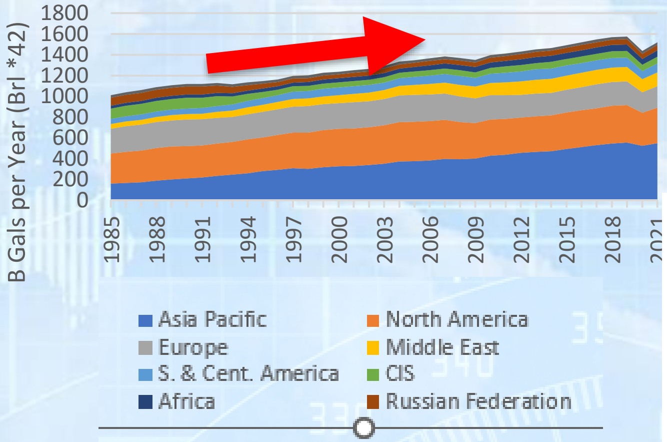
- US Aviation 18B Gas 135B
- World Aviation 96B gals
- US Gas 135 /1400=10%
- World Avi. 96/1400 =7%

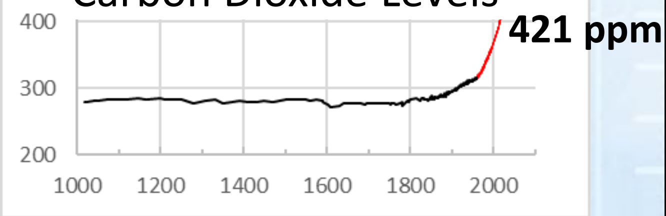
World 2021
~35 Billion barrels*42=
~1400 Billion Gals/yr

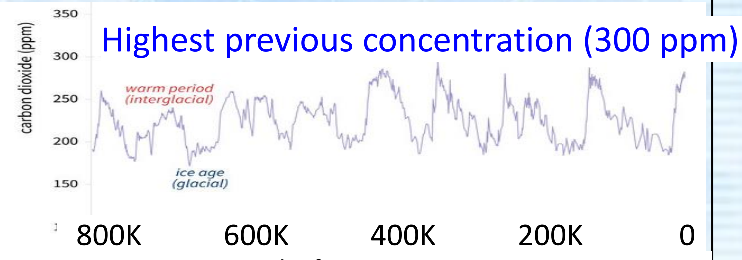
EPA reports that commercial airplanes and large business jets contribute 10% of U.S. Transportation emissions, 3% of total green house gas

2009 Products Made-per Barrel Crude Oil (gals)
20 Gas 10 Diesel 8 Other
4 Jet=42 gal/brl 4/42 10%

World Oil Consumption by Region





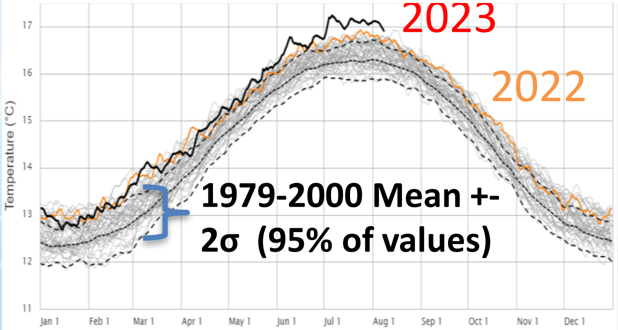


NOAA climate.gov

CO2 lbs per gal
Gasoline 19.6 lbs
Diesel 22.4 lbs

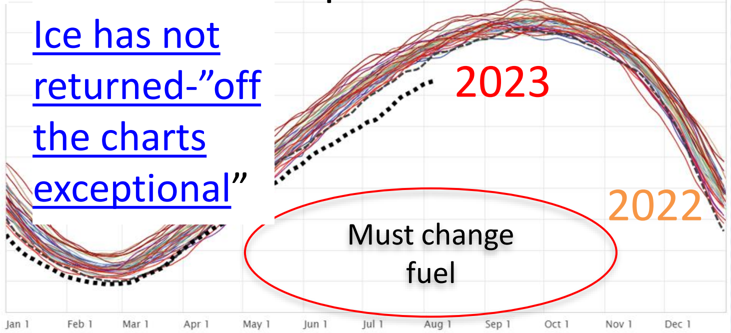
It takes centuries for CO_2 to be absorbed by Earth and continues to warm even at ppm

Daily 2m Air Temperature*



Southern Hemisphere Sea Ice Extent*

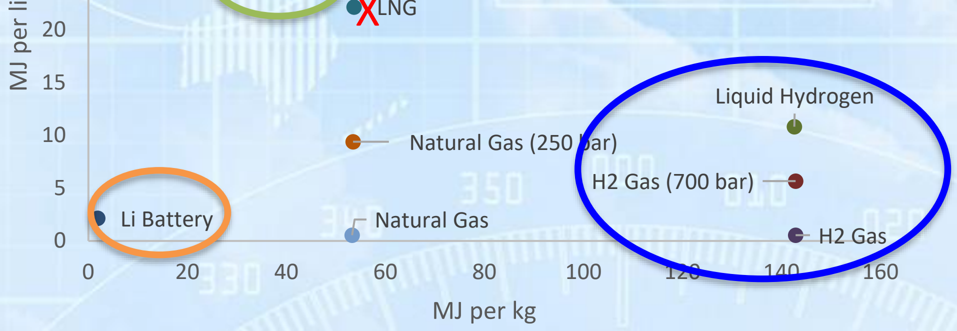
Ice has not returned-"off the charts exceptional"



*Birkel, S.D. 'Daily 2-meter Air and Sea Surface Temperature, Sea Ice Extent', Climate Reanalyzer (https://ClimateReanalyzer.org), Climate Change Institute, University of Maine, USA. Accessed on August 8, 2023.

Hydrogen: Low Energy per Unit Volume

- **100% LH2 powered aircraft requires 4X more fuel volume compared to conventional**
  - Heat Combustion: LH2: (51,590 Btu/lb)/ JP(18,400) = 2.8
  - Density: JP (50.6) /LH2: (4.43 lb/ft3) = 11.4
  - 11.4/2.8 = ~4 times LH2 fuel volume vs conventional
- Low energy per unit volume introduces significant challenges to economically meet the stringent aviation mass, volume and safety requirements
- Examples to follow



X Methane leakage was 7 times higher than EPA estimates of 1.4 percent Permian

Methane leakage is destroying the hydrogen economy , increasing Direct Air Capture Costs and ~20% net forcing. At 3% leakage, CH4 is worse than coal.

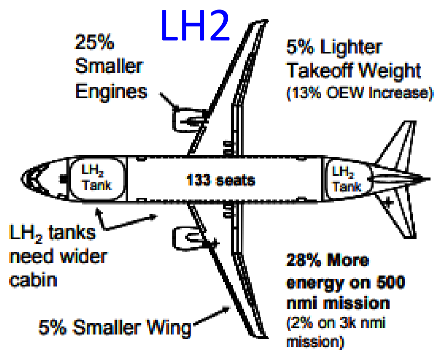


Figure 13.—Hydrogen-powered airplanes need a larger tank, which reduces the fuel efficiency of short-range aircraft.

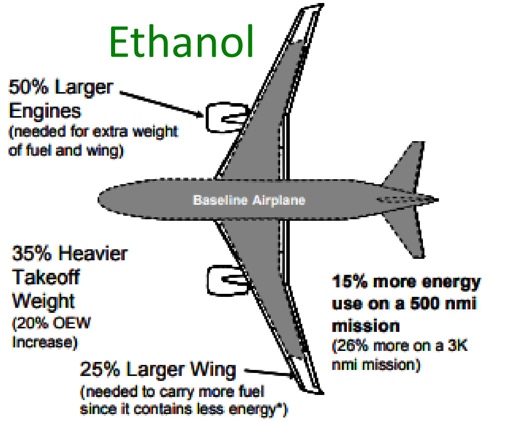


Figure 14.—An ethanol-fueled airplane requires a larger wing and engines, thus reducing the airplane's fuel efficiency.

https://ntrs.nasa.gov/api/citations/20060051881/downloads/20060051881.pdf

SAF Status and Challenges

GAO, May 17, 2023: Still Only 0.1% of U.S. aviation supply
"SAF-used at 2 airports, less than 0.1% of jet fuel of U.S. airlines."

- ***Feedstock limited SAF (HEFA)** ~2X Jet Fuel $/kg; **Alcohol to Jet** 3-6X ; **PtL** 3-6X*
- **E-Kerosene (Ptl)** 7-10x cost of Jet A; DAC+H_2 – no feedstock limitations

	Feedstocks – Synthetic Aviation Fuels
HEFA	Hydroprocessed esters fatty acids-Oil crops
Gas-FT	Feedstock Gasification (solid waste, cellulosic)
AtJ	Alcohol-to-jet (corn, sugarcane, cellulosic)
Ptl	Power to liquid (green LH2+carbon capture

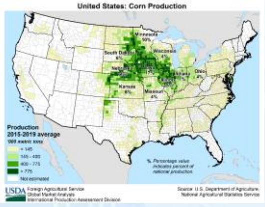
ASTM D1655, D7566 Standard Specifications for Aviation Turbine Fuels - global basis jet fuel quality specs-crucial role ensuring operational safety, reliability

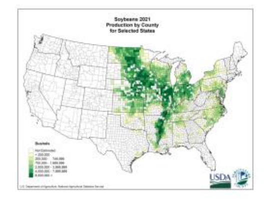
Direct Air Capture-- why so expensive?
240-300 MW captures 1MtCO_2/year (~$240/Mt$CO_2$) $417/tCO2 $300-400
- Upstream natural gas leakage dramatically increases this cost
  - 86- GWP20 (20-year time horizon) 32-GWP100 (100-year) for CH4

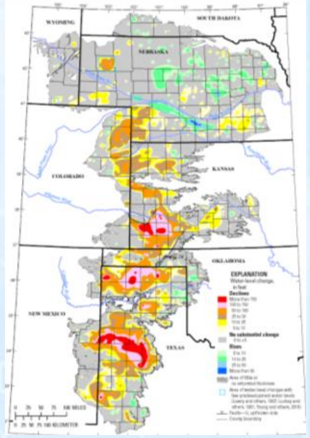
- Nat. gas less expensive than electricity for same thermal out
- Electric Calciner cannot cycle; needs storage via wind/solar (adds 8¢/kWh)
- Less CO2 concentration, higher costs –coal not capturing CO_2
- Exhibit 21 Euro H2 Study $240/Mt$CO_2$

Texas managed depletion of Ogallala Aquifer is 6.5x its recharge rate. Fracking-16M gal per well

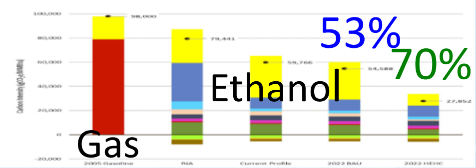
Data to 2015



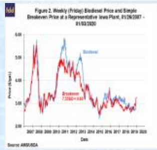




Ethanol: 47% less GHG vs gasoline-Land Use,Fertilizer, Practices Key-CH4 leakage?



Biodiesel $3-6/gal
2007 to 2019
1.5-3X Jet A $/gal



Irwin, S. "Biodiesel Production Profits in 2019." *farmdoc daily* (10):21, Dept. of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, Feb 5, 2020.

Ideal free conversion of Ethanol to Jet A
- Ethanol $2.40/gal, Jet A ~$2 → **1.2x $/kg ideally**
- Ideal Emissions:0.60*0.47+0.4*0 =**0 to 28% less CO_2?**
  - U.S. 18B gal/yr⇔U.S. Av. 18B gal @60% energy = 0.60
- Does not consider water availability, land, other feedstocks, grade fuel produced, methane leakage
  - US, Brazil dominate Ethanol Production
  - Rainforest destruction soars 2022

"US High Plains produces more than 50 million tonnes of grain yearly and depends on the aquifers for as much as 90 percent of its irrigation needs. Taken as a whole, therefore, the model shows that **continued depletion** of the High Plains aquifers at current levels represents **a significant threat to food and water security both in the US and globally**. Grain production in Texas could be reduced by 40%."

DAC, CO2 to Jet Fuel

- Aug 2023 DOD converting CO_2 into Jet Fuel small mobile fuel production systems
- Aug 2023 $1.2B for two Direct Air Capture Plants ($3.5B by IRA)
- The processes: Transforming carbon dioxide into jet fuel
- Review of GHG Emissions of Corn Ethanol under the EPA RFS2
- Cost Analysis-Carbon Capture and Sequestration Industry ; $300-400
- SAF is “the only answer between now and 2050.”

E-Kerosene for Commercial Aviation

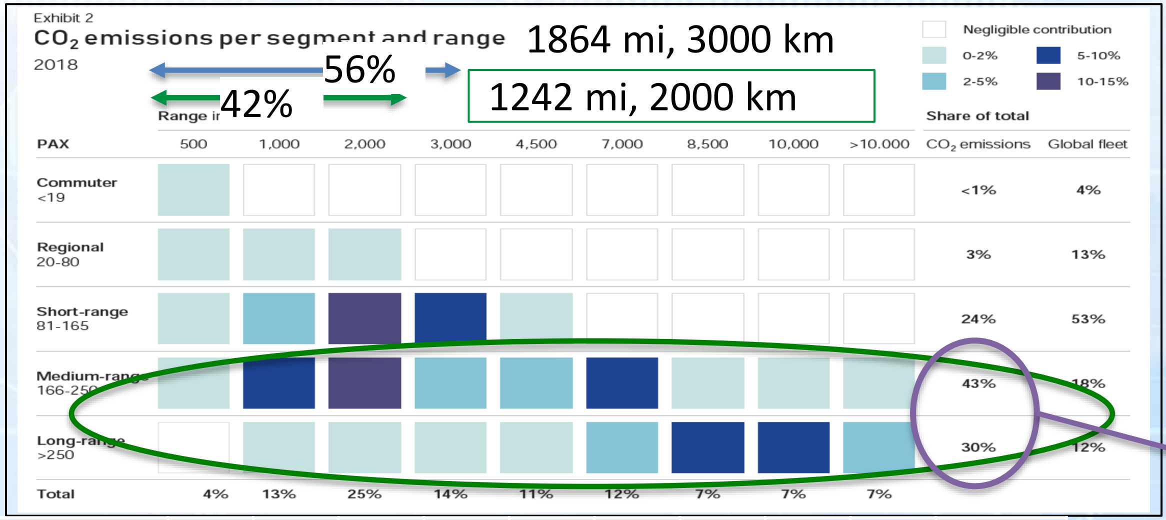
- Large scale domestic production of SAF requires renewable energy
- Short-haul favors batteries- require less energy per nm than fuel cells or hydrogen combustion
- Green hydrogen will always take less energy than DAC-ekerosene (PtL)
- **2050 jet fuel demand with four year rotation crops would require the entire arable land capacity of U.S. and ~3X the sustainable arable land in Europe**
  - DAC-kerosine is projected to be 44% to 55% of commercial aviation sector by 2050 assuming **available renewable energy** and **2.7c → 1.6c/kWh**
  - energy storage for calciner vs capital costs? **Available renewable energy if 3x LH2?**

Sustainable Aviation Fuel - Current Status

Alternative Aviation fuel faces resource limitations, significant energy usage and capital, and lack of renewable energy to reduce emissions economically- 2050 SAF goals are unsustainable

- SAF from four-year rotation crops
  - Emissions are only reduced 28% to 0% (CH_4 leakage) to meet current US demand of 18B gal/year shifting ethanol to jet fuel production, but does not consider water, renewable energy, or other feedstock availability
  - 2050 World jet fuel demand would require the entire arable land capacity of U.S. and ~3X the sustainable arable land in Europe; US and Brazil dominate ethanol production
    - Rainforest destruction soars in 2022, Aquifers are being depleted
- Alcohol-to-Jet is 3-6 times the cost of Jet Fuel, feedstock limited HEFA ~ 2X Jet Fuel Cost
- Power-to-Liquid (PtL or e-kerosine) via Direct Air Capture is 3-11 times the cost of Jet Fuel
  - $300-400/mtCO2 projected vs European Study $240/tCO2eq dropping to $150/tCO2eq abated
- SAF production is currently 0.1% of U.S. aviation supply used at 2 airports
- Industrial capture and sequestration may provide limited quantities of lower cost carbon
- $3.5B Hydrogen Hubs and $1.25/gal subsidy may change outlook-SAF Grand Challenge in progress
  - Must include effects of methane leakage

CO2 emissions by flight segments and Market



Total	4	13	25	14	11	12	7	7	7	
Cumul Total %	4	17	42	56	67	79	86	93	100	
% 2080 km	100%	100%	100%	69%	46%	30%	24%	21%	21%	1242 mi
Total%2080	0.04	0.13	0.25	0.10	0.05	0.04	0.02	0.01	0.01	65%
Cumul. Sum	0.04	0.17	0.42	0.52	0.57	0.60	0.62	0.64	0.65	

CO2 emission reduction with 2080km of LH2 onboard

2023-2042 Boeing Forecasts Demand for 42,600 New Commercial Jets valued at $8T

NEW DELIVERIES (2023-2042)	
Regional Jet	1,810
Single Aisle	32,420
Widebody	7,440
Freighter	925
Total	42,595

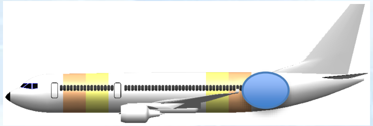
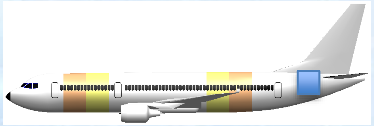
Medium- and Long- Range Aircraft contribute 73% of CO2 emissions
25%/30% CO2 long range > 3,000km 1,864 mi

- **42% of emissions occur in flights less than 2000km** 56%-3000km 67%-4500 km 79%-7,000 km
- 100% Short range LH2 aircraft viable by ~ 2035 Euro Study - 4,500 km, 2800 mi range

- **Add 2080 km (1300 mi) of green hydrogen to all aircraft** e.g.-Medium Range 2080/6574 km ~ 32%
  - ***42% of flights have zero CO2 emissions***
  - ***60 to 65% CO2 emission reductions with 2080 km range of net zero fuel***
  - **50 to 55% CO2** of emission reductions excluding long range aircraft
  - ***Medium-range aircraft with 2080 km of net zero range eliminates 30%/43% or 70% of total emissions***

Dual Hydrogen-Jet Fuel Aircraft

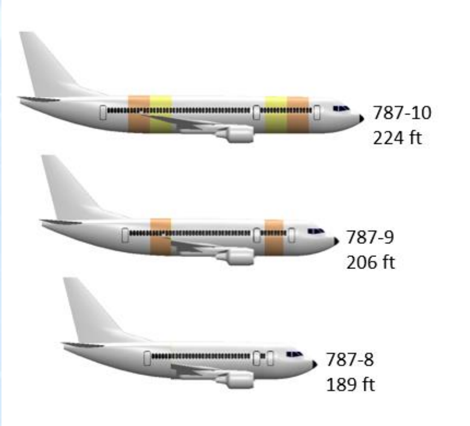
- **Concept:** Retain Jet A wing tanks
  - Add H2 fuel, remove Jet A gals of equivalent energy

Variation of center of gravity introduces stability challenges

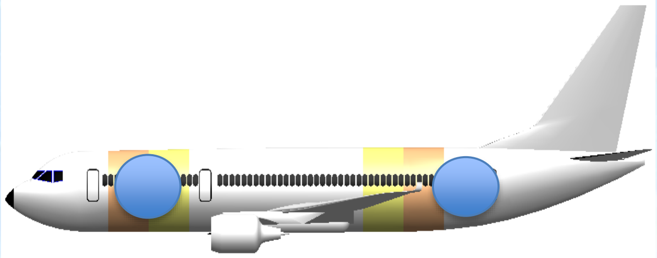
APU-5%

787-8 PAX to -10



Fly 787-8 PAX in a 787-9, -10

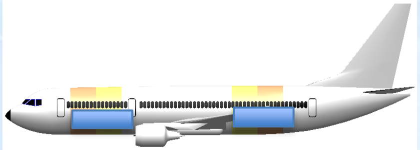
Remove 777 PAX add Tanks



Forward Low, Aft tanks maintains center of gravity during flight

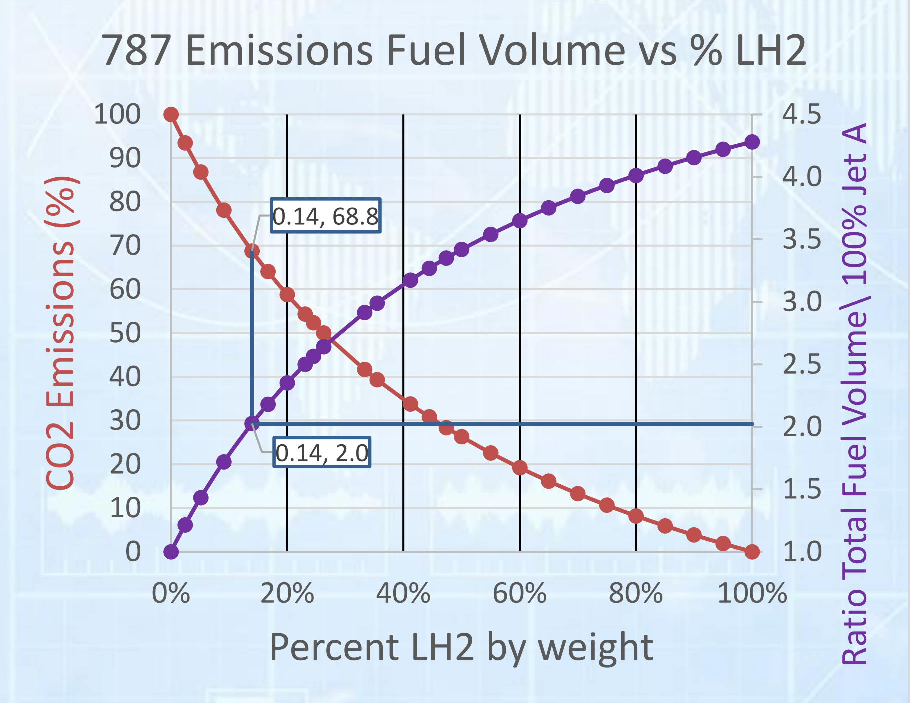
If tank+fuel weight less than displaced cargo – limited fuselage modifications

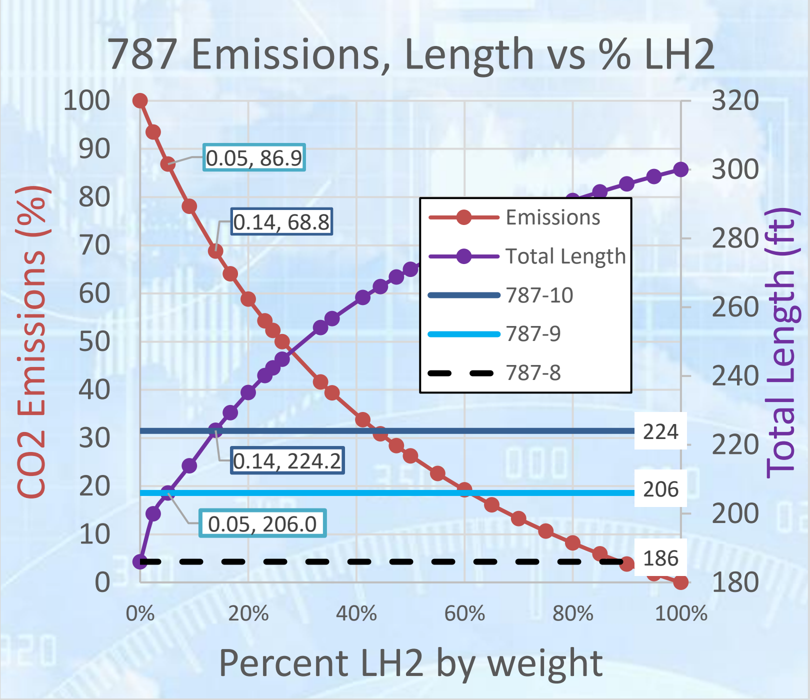
737 Cargo Bay

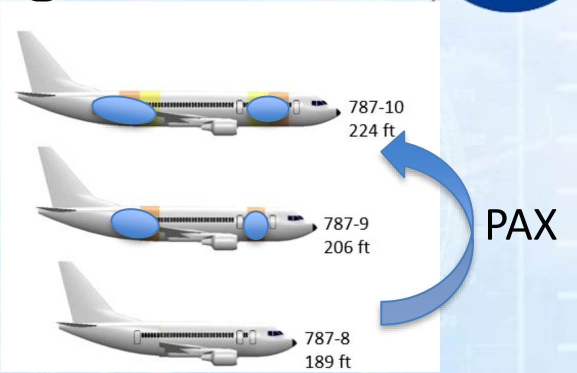


	737	777 / 787	777 / 787
PAX/row	6	8	9
Wt+ Bag	205	205	205
Seat	25	25	25
Lbs/row	1380	1840	2070
Pitch(in)	32	32	32
PAX lbs/in	43.1	57.5	64.7
Cargo (lb/in)	28	28	28
PAX-Cargo lb/in	71	86	93

Shift 787-8 PAX to -10 - Long Range







~ 30% by energy LH2 fits
Minus 27% PAX
30%range=2220mi, 3570km
34 meters for 100% LH2?
→ Others ~ 20m meters
*First Order– No Aircraft Design
787-8 33,528 gals

	L(m)	L(ft)	dL (ft)	PAX	PAX dif	%LH2	PAX %	% Fuel	% Cost	dCO2	Tank Vol	TOW	JA1 Range
787-10	68.3	224	38.1	330	88	**13.9%**	27%	3%	**30%**	31	2.02	**509084**	nm **6430**
787-9	62.8	206	20.0	290	48	**5.1%**	15%	3%	**17%**	13	1.43	**509038**	7635
787-8	56.7	186	0.0	242	0	**0.0%**				0	1.00	502500	7355

Currently, 787-10 is 57,500 lbs more than -8 MTOW (***560,000*** vs 502,500 lb)
Adding LH2 reduces overall fuel/tank weight, less PAX weight
Long Range is a significant challenge to expand, extend OD

- 787-8 to -10

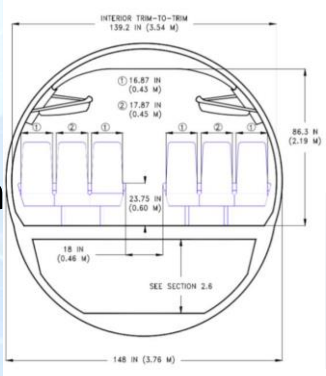
-88 Pax, 31% dCO2, 30% Operation Costs

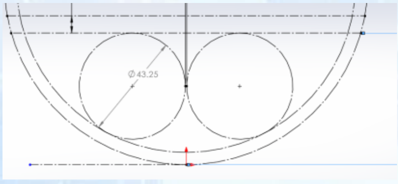
		nm
Japan	hawaii	3510
Chicago	Hawaii	3645
NY	London	3008
NY	Hawaii	4309
LA	London	4728

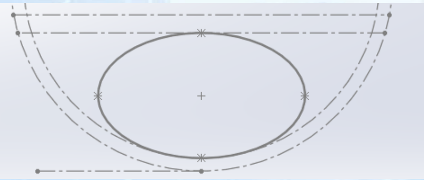
Fuselage lbs/ft	255
Fuselage LH2 Penalty	3.8
Fuselage LH2 lb/ft	969
Tank/Fuel Mass Ratio	0.4

737 Fill - Cargo Bays

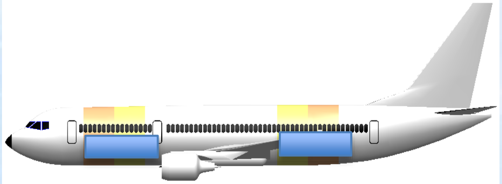
- 2 Cylinders inside 43” (x2)
- Fore/Aft bay length 25’
- 6875 gals –3800 mi 3300nm 6100 km
- **14%** 6” thickness for tank/support
  - 3920 gal LH2   (-971gal–Jet A)
- **22%** 2” thickness
  - 6530 gals LH2 (-1527gal Jet A)
- Elliptical Tank (x2):
  - 8400 gals LH2 (-2070 Jet A)
  - 3” thickness **30%**
  - 5” thickness **25%**



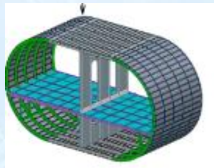


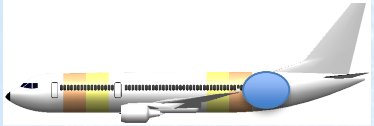


Cargo Bay: **14- 34**% Less CO2
32% LH2 is a challenge for Small Cargo Bay dimensions even for elliptical tank
Double D Fuselage?



Raise Floor 6”
Elliptical (+6” floor) **30%**
Raise Floor 10” (50” OD)
2” thickness **34%**
6” thickness **21%**
Double D fuselage?





Adding fuselage sized tank(s) aft increases A321 length 9m

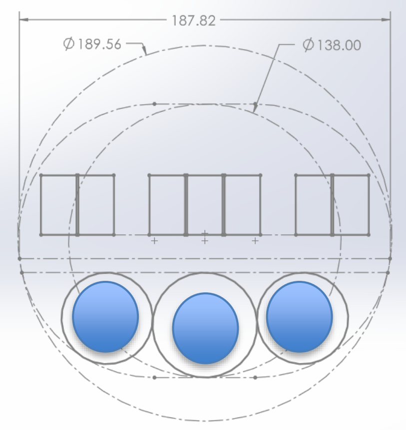
As of July 2023, the 737 MAX has 4,339 unfilled orders and 1,276 deliveries.

737-8 4086mi 3550 nm
32% 1292mi 2080 km

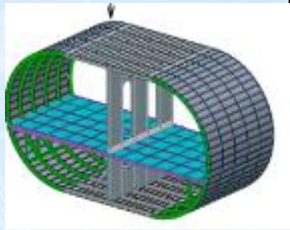
Double D fuselage and SUGAR Truss Brace Wing

3-3 to 2-3-2 or 2-2-2

Double D fuselage Forward Only, transition to cylindrical aft to balance fuel burn CG. Adds seats to offset PAX removal for tanks?

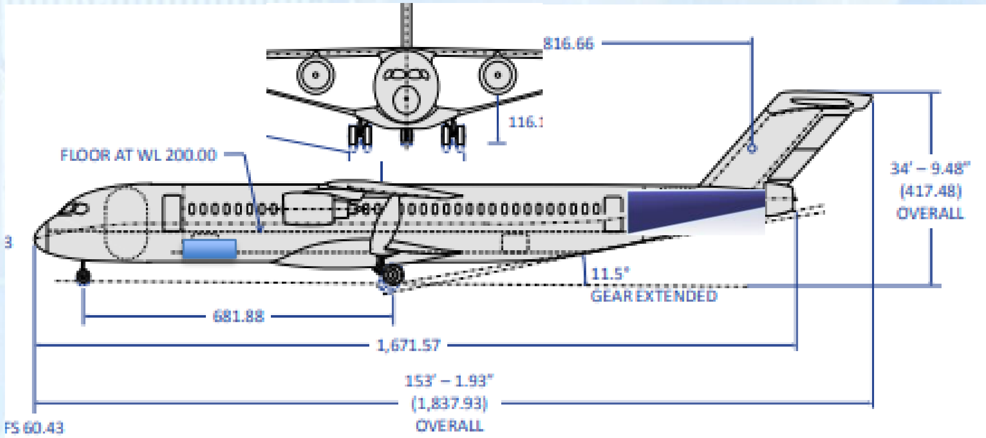


Add row+aisle, 2 seats in middle are wider to accommodate center support

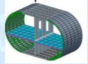


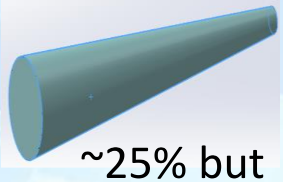
Double D fuselage **~15%** in 3 tanks forward – 25'

Gas turbines can operate over a wide range of H2 %.



SUGAR Truss Braced Wing + Cryogenic tanks

Double D fuselage  Forward **~15%** in 3 tanks



~25% but removes door – lengthen 2-3m

+Aft cylinder **25%** = **40%**

Medium Range is 43% of CO2 emissions

MD-90 conversion to X-66A Truss Brace Wing – Sustainable

At the tail: BLI-Aft Fan, APU, Tri-Jet?

Double D Fuselage Forward increases tank volume, reduces c.g. shift, access 40% LH2 if SUGAR TBW (~ 737 size) is lengthened 2-3m, 100% LH2 ~ 10-15m

Green Hydrogen vs SAF Fuel Costs

- **Hydrogen $3/kg, 1.5-1X Jet A**
  - If you buy PV wholesale afternoons when demand is low, supply is high (excess power) "Duck curve" (no 'storage' required)
  - **IRA $3/kg subsidy = "free"**
  - Assumes PEM not SOEC fuel cells
- Feedstock limited SAF-HEFA is 2x Jet A
- Alcohol to Jet, Power to Liquid (PtL) 3-6x Jet A
- E-Kerosene (Ptl) 7-11 x Jet A
- **What are costs, availability of renewable energy?**

2021 Optimizing an Integrated Renewable-Electrolysis System (nrel.gov) (assumes PEM)

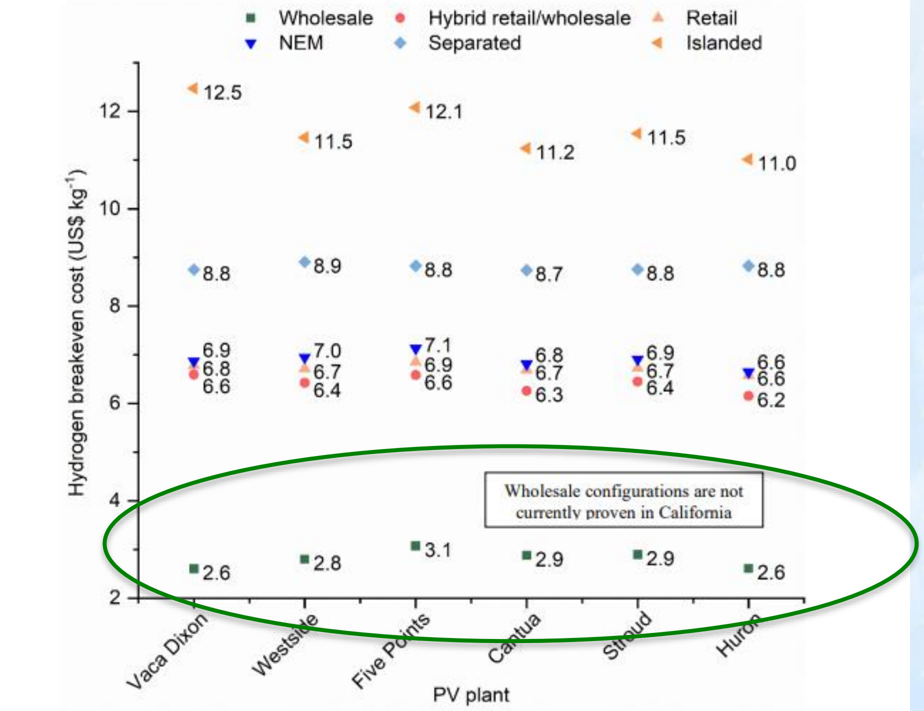


Figure ES-2. Current hydrogen breakeven production cost for PV + Electrolysis systems with six market configurations and six candidate locations

04 May 2023 Bloom Energy demonstrates H_2 production with solid oxide electrolyzer at NASA Ames

This high-temperature, high-efficiency unit **produces 20%–25% more H_2 per megawatt (MW)** than commercially demonstrated lower temperature electrolylzers such as proton electrolyte membrane (PEM) or alkaline. The current demonstration expands on Bloom's recent project on a 100-kW system located at the Department of Energy's Idaho National Laboratory (INL).

Wind, Solar, and Gas have all levelized to \$0.03/kwhr

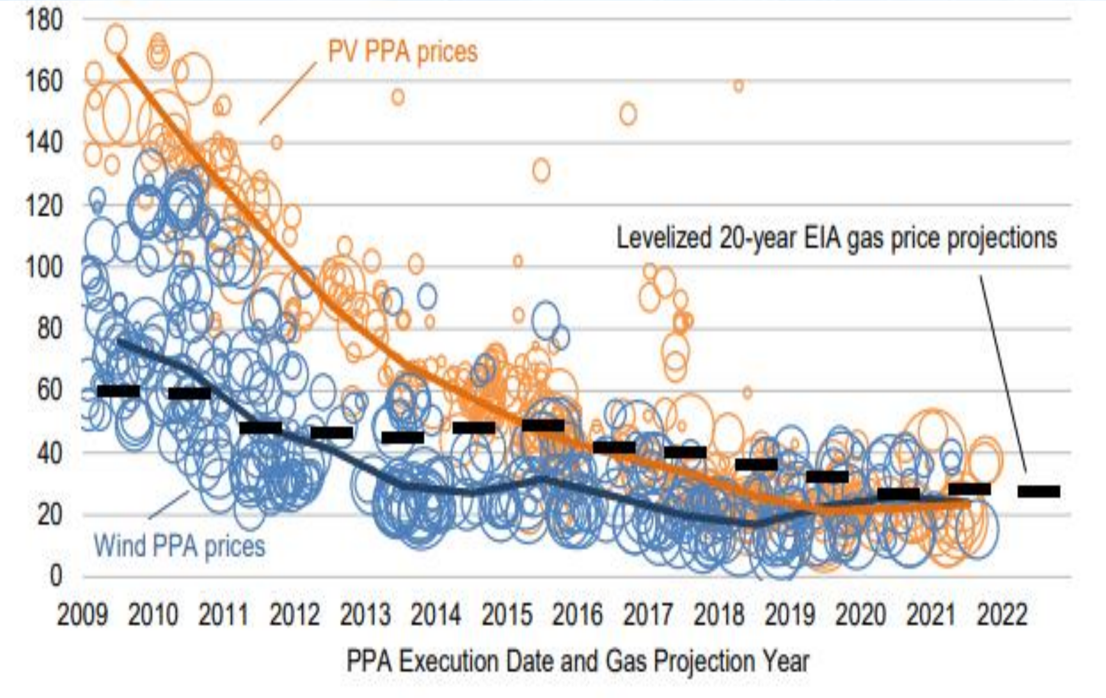
- U.S. Cents/kWh:
  - Solar 3.4 (+Storage 11), On-Shore 4.2, Fixed off-shore 4.8
  - Coal 18, Natural Gas 8.6 -> 3
  - US: 13.15 Ohio 14.33 ¢/kWh
    - Why so high?
- Offshore wind can produce far more power than onshore, but floating costs must fall substantially

Purchase Agreements→ renewable energy costs sufficient for low cost H2

What about the grid?

Levelized Power Purchase Agreements 2021 MWh

energy.gov



It is about 10 times cheaper to transport energy by a hydrogen pipeline than by an electric cable

1000 miles: 0.5¢/kWh for H2, 5¢/kWh grid

Grid Overhaul Underground?

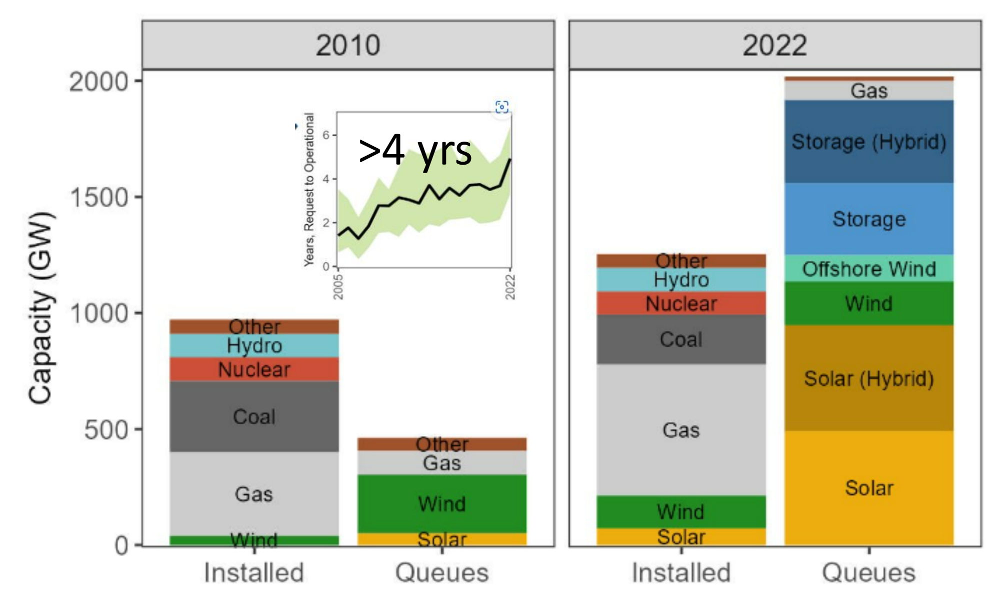
Renewables face Multiple Bottlenecks, Connection Requests up 40%

- U.S. has 1,250 GW capacity -> 2000 GW in queue exceeds entire capacity of US power plant fleet
- Renewables face HUGE interconnect fees and wait times- 2 years (2000s) to over 4 years today

- US Grid- patchwork of 1000s local utilities who do not account for long-term benefits and lower costs
- Geothermal can significantly reduce electrical demand, methane leakage - need vertical drilling

- Offshore Wind does not have a plan where to go
- Offshore can produce far more power than onshore wind, but floating costs must fall substantially

- Off-Grid Power Will Be Our New Norm- 'local' renewable future market decentralized reduce costs
- Lack of battery materials limits EV growth *Debt bill reduces federal environmental permitting to 2 years*



Grid Connection Growth and Backlogs- Berkeley Lab

- Over a decade to install 6 Lake Erie wind turbines
  Cats, Buildings, Pesticides, Fossil fuels kill more birds than wind; Minimal on Lake Erie as birds often shun direct migration across water
- 71 Turbines Approved July 2023 after 'poison pill'
- NY Great Lakes Wind - Ports, grid connection
- Great Lakes Wind

Hydrogen Aircraft, Safety, and Emissions

- Requirement for **well-insulated, sealed, cryogenic tank and fuel system including infrastructure** represent challenges to the designer and **now require flight demonstrations** to raise technology readiness
  - Start between two airports just like SAF

- **Cryogenic systems and infrastructure do not pose an insurmountable problem** for **dual hydrogen-jet fuel aircraft**--learn from the demonstrators, find the unknowns
  - Safety assessments based on decades of experience require designs and hardware
    - Hydrogen Aircraft – Brewer
    - Comment: Addressing the challenges of hydrogen-based aviation
    - An assessment of the crash fire hazard of liquid hydrogen fueled aircraft Little 1982
    - Safe Use of Hydrogen and H2 Systems – NASA Safety Training Center 2006 - Hindenburg Misconception
    - How Hydrogen Compares to Jet Fuel in Terms of Safety

- **Reducing Climate impact economically and safely is a massive prize**

  60% emission reduction if all short-, medium-, and long-range aircraft have 2080km of net-zero range

Hydrogen Warming Potential and Contrails

- Methane Leakage is limiting the hydrogen economy ; methane is key driver of warming
- Boils down to one molecule hydroxyl radical (OH) "the detergent of the troposphere"
- OH-critical role eliminating methane, ozone
- Limited amount OH generated each day, any spike in hydrogen leakage means OH would break down hydrogen, less for methane and ozone breakdown
- Methane leakage <0.5% allows H2 leakage < 4.5% (Methane leakage has been over 10%)
- Global Warming Potential of Hydrogen is 11;
  - Methane is 25-40 GWP
  - 86 GWP20 (20-year time horizon) 32-GWP100 (100-yr)

SAF, H2 vs Jet A reduce Contrails

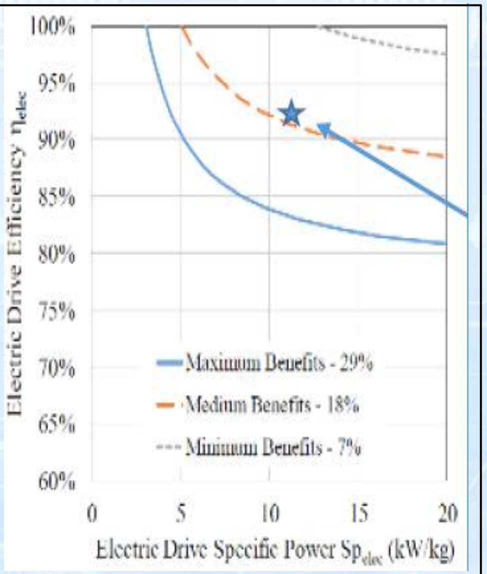
Carbon dioxide life cycle however is 200+ yrs

- Global Aviation Net Emissions Net forcing, with uncertainties, now has contrails higher than emissions
  - **Contrails 57.4, (51.8 = CO_2 34.3 + NO_x 17.5) mW/m²**
  - Jet Engine emits 3.16kg CO_2, 1.23kg H_2O per kg fuel, soot
  - *Higher Clouds colder-block more radiation to space*
- Contrails mostly form above 30,000 ft, higher humidity
- SAFSs produce 50-70% fewer, larger ice crystals due to lower aromatics ***Fewer ice particles with SAF, diameter increase-> shorter life***
- Burning Biodiesel (HEFA) at altitude better than semis
- *Ice crystals are predicted to be larger for H2 engines and even larger for H2 fuel cells reducing Contrail forcing*
- *Modifying flight altitude and paths cut contrails 54% with 2% more fuel burn*

Adding Electrical Power Enables Multiple Configurations to Reduce Fuel Burn

- LH2 offers ‘free’ cooling to improve power conversion efficiency, improve engine life, fuel cell efficiency, further reduce fuel burn

<u>Propulsive benefits drive required electrical system efficiency and to lesser degree kW/kg</u>



<u>Aft Fan</u>

Ingest more turbulent, slower moving boundary layer (BLI) and accelerate to produce thrust- APU?

<u>Blended Wing Body</u>

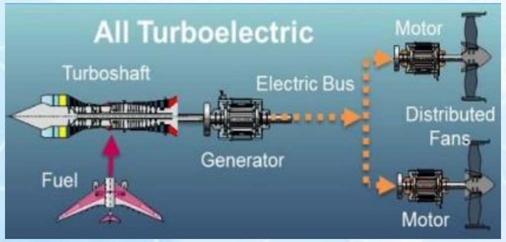
Multiple Distributed propulsors – stability without <u>control surfaces</u> (engines only -inefficient),
Boundary Layer Ingestion
High Bypass Ratio – decouple shaft speed
“Cut tail off” - less drag (not stable). Best for LH2?

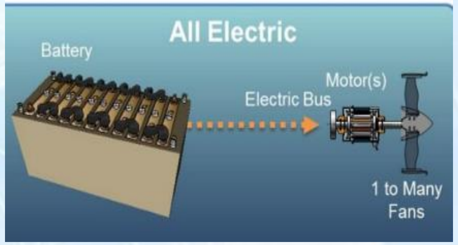
<u>Air Force Tanker - Jet Zero</u> Demonstrator

<u>Transonic Truss Braced Wing Demonstrator</u>

Increased wing aspect ratio- less drag
Many challenges to develop
→ Add partial LH2 to demonstrator

Wed AM E&M Sustainable Aviation Exhibits





<u>Many Powertrain Configurations Present Different Challenges</u>

Copper vs Superconductor AC Loss

- Efficiency is key metric and to lesser degree kW/kg
- Lower AC loss improves system metrics, reduces machine design complexities

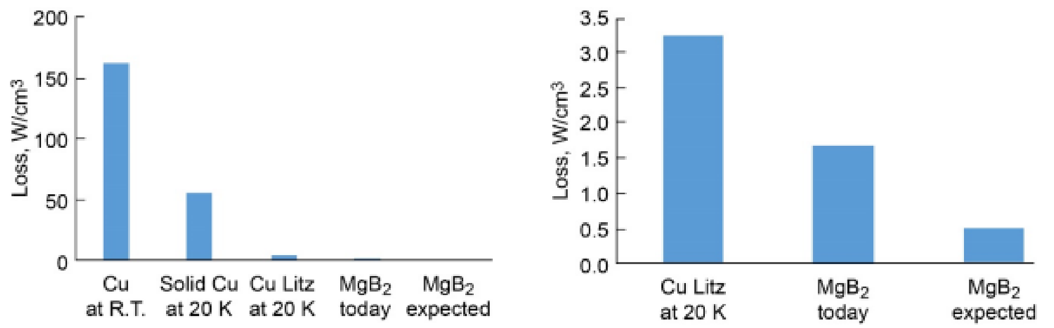
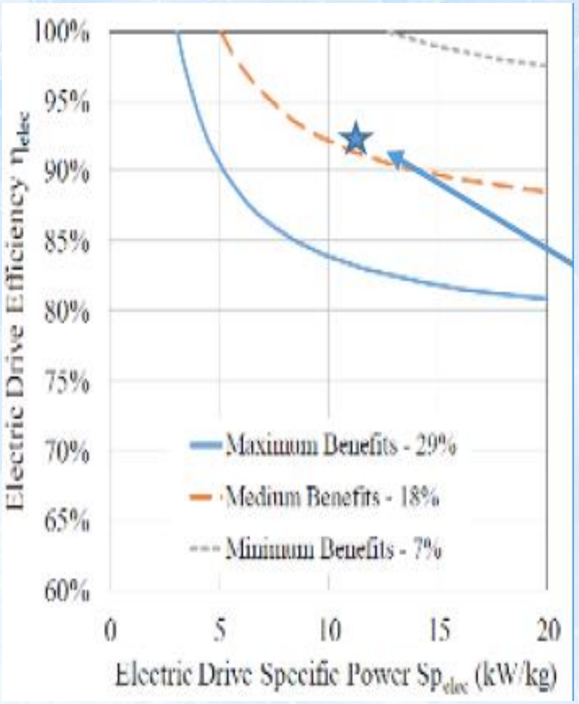


Figure 17.—Losses in various copper and MgB_2 wires. All wires are 0.96 mm in diameter and carry 100 A operating current in an AC magnetic field of 0.5 T at 200 Hz. Solid copper case at 20 K includes 12 percent magnetoresistance plus large eddy current loss. Copper Litz wire has 100-μm filaments. Room temperature (R.T.).

Figure 18.—Losses of cryogenic copper Litz wire and MgB_2 wires.

Propulsive benefits drive required efficiency and to lesser degree kW/kg

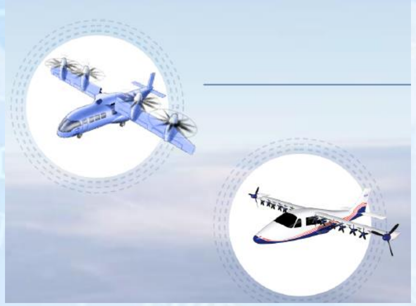


https://ntrs.nasa.gov/api/citations/20205005815/downloads/TM-20205005815.pdf
https://www.energy.gov/sites/prod/files/2020/12/f81/hfto-h2-airports-workshop-2020-schneider.pdf

New Business Model Driven by Emissions?

- <u>Current: Revenue PAX km ($ per passenger-km)</u>
  - What about fuel efficiency?
  - Long haul average is 31.5 PAX-km/liter
  - 27 to 40 PAX-km/liter is variation of all airlines

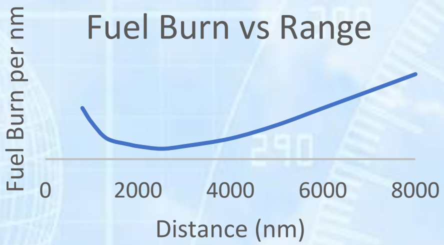
Larger Volume?



Batteries /Fuel Cells for short trips?

- Fuel consumption is 3-4 liters per 100 PAX-km
  - Autos 8 (2000) → 5.4 (2016) liters per 100 PK
  - Aircraft lower if fully packed and a bit faster too

- <u>En-route stops vs non-stop can reduce Fuel per PAX-nm</u>

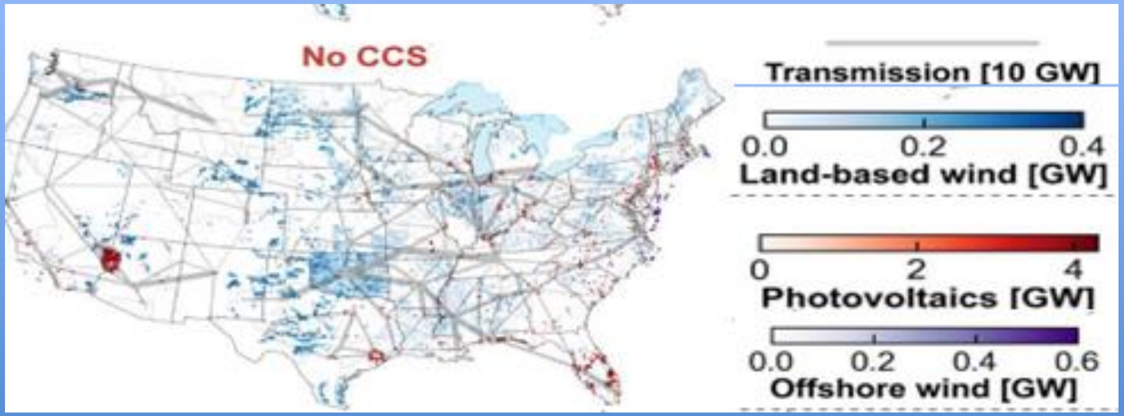


Reduce number or add stops to long-range flights where practical?
42% of emissions occur in flights less than 2000km
25% of 30% CO_2 emissions in long range segments > 3,000km 1,864 mi

<u>BWB for Air Force Tanker - Jet Zero</u>
Demonstrator retire elliptical shape and stability risks?

Hydrogen can act as storage and help reduce grid bottlenecks

US net zero plan doubles grid and generation (~70% wind/solar), targets ground transport, hydrogen blends aids seasonal storage needs.



Wind Solar Land is available for other uses (Corn, Buildings, railroads, coal)

It is about 10 times cheaper to transport energy by a hydrogen pipeline than by an electric cable

1000 miles: 0.5¢/kWh for H2, 5¢/kWh grid

Grid Overhaul Underground?

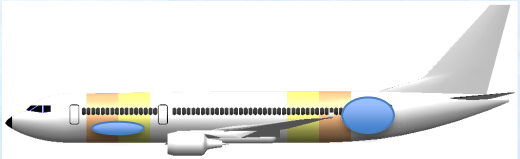
- *Adding LH2 tank reduces total footprint and emissions per revenue passenger km of entire dual fuel fleet*
- *Adding LH2 tank provides early, gradual transition to work challenges, details and economics of a radically different transportation system*

Tough to decarbonize Industries and transportation - Hydrogen Pull Applications

- Cement 8%, Steel 4%, Aviation ✈ 3%, Ships, Long Haul
  - Large facilities producing hydrogen can be switched on or off as supply of electricity fluctuates could be key to reduce high emission industries and economically consume excess capacity to reduce grid bottlenecks and distribution costs
- Cement 8% of emissions -Waste Heat Recovery Opportunity Of many options, produce green H2 on site; integrate with Electrolysis to improve efficiency
- Steel 4% - Potential of hydrogen to decarbonize (up 30% in costs)
- Engineers have modified conventional diesel engine powered by hydrogen and small amount of diesel to cut emissions 85%
- *MIT reversed SOFC degradation and enhanced performance*

Dual Hydrogen-Jet Fuel Aircraft

It's the volume induced PAX costs, grid bottlenecks



- 30% LH2 by energy doubles the fuel volume of Jet A aircraft
  - 2080 km of zero emission range provides 50% emission reductions
- it's best fit economically, reduces certification demands,
  - More stable fuel costs than SAF and Jet kerosene with unbounded supply
  - Lower maintenance costs. Boost Range for electric vertical take-off and landing
  - need new configurations, less fuel burn
- LH2-cost competitive with Jet Fuel today-significantly less emissions
  - $3/kg subsidy – "free"; Liquefaction likely $2-3/kg, scaling dependent, at airport
- H2 via pipelines reduces transport costs – locate near other Pull apps
  - <u>It is about 10 times cheaper to transport energy by a hydrogen pipeline than by an electric cable</u>
  - trade pipelines versus electrical grid transport
- Need real world test data, technology to include more LH2

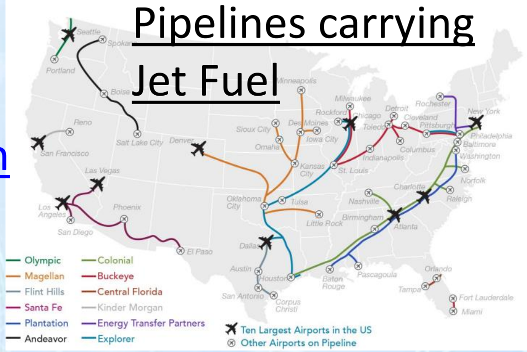
Where to Place H2 Hubs?

Off-Grid/Excess Renewable Power to Economically Reduce Emissions

- Near Airports, Steel, Cement, Transport and Renewable Energy
- Need studies to examine H2 pull locations (airports, steel, concrete) near excess power (land and offshore wind, solar), near interstates and existing aviation, gas pipelines
- <u>Natural gas pipelines are limited to ~5-10% hydrogen</u> – <u>H2 needs "natural gas" designation</u>
- <u>diesel / 90% H_2 can be combined- without significant NOx-</u> Long Haul Transport, <u>mining</u>

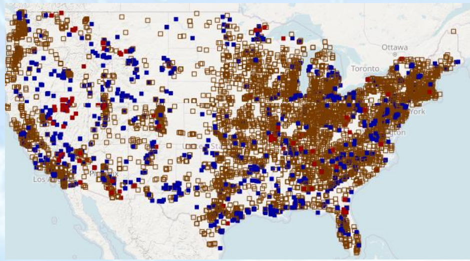
[It is about 10 times cheaper to transport energy by a hydrogen pipeline than by an electric cable]

<u>Pipelines carrying Jet Fuel</u>



Hydrogen acts as storage for excess renewable energy

- Connects SW Solar (duck curve excess power)
- Connects land and offshore wind
- Grid – pipes and/or HVDC? Along major interstates?
- Optimize to reduce transmission costs, bottlenecks



<u>Active mines and mineral plants in the US</u> – more cost effective to transport hydrogen to sites?

<u>10 to 35 Airports – Top 200 O-D Zonal Flows by Air</u>
Hydrogen demand in fixed and fewer locations

Dual H2-Jet Fuel Aircraft Vision and Strategy

- **2023 Dual Hydrogen Jet Fuel Flight Demonstration**
  - Demonstrate that short and medium range aircraft and infrastructure can reduce emissions 50% economically adding hydrogen to identify new or resolve challenges within stringent mass, volume, and safety requirements
- **Vision Forward is that emissions will be decreased sooner and economically through**
  - Dual H_2-Jet Fuel Aircraft reduce emissions 50% with only 2080 km of range and certification time
  - Providing partial pull to build out H2 infrastructure in fewer, fixed locations– cargo configs first (?)
    - H2 less cost than SAF. Supply limited only by renewable energy availability (off-grid, decentralized power)
  - Adding H_2 Airport liquefaction hubs annually, adapt to tech maturation, lessons learned
    - Introduce efficiency gains with liquefaction: provide low quality heat for buildings vs cooling towers
  - Building H2 plant locations near Pull applications (airports, concrete, steel, transport)
    - 10 times cheaper to transport H_2 in pipeline vs cable ; Liquefaction as close as possible to aircraft (transport costs)
    - LH2 acts as energy storage, buy cheap excess energy (duck curve) to address grid cost and transmission solutions
    - Aid offshore wind connection plan, and develop microgrids and H2 pipelines to address energy transport costs
  - Development of new technology and different aircraft configurations required to meet Net Zero
  - By retaining the wing tanks, it does not preclude SAF Aviation Climate Action Plan Vision

Aircraft Design/Infrastructure/Power/Carbon SAF

Aircraft Design

- B-57 switched to LH2 powered flight over Lake Erie in 1956 with existing engines-first dual hydrogen jet fuel aircraft demonstration
  - Requirement for well-insulated, sealed, cryogenic tank and fuel system represents a challenge to the designer now requires flight demonstrations to raise the technology readiness
  - Cryogenically insulated systems do not pose an insurmountable problem for dual fuel aircraft; must minimize heat leaks, and provide flight-weight tanks, withstand 1000s of take-offs and landings, address safety and certification of a radically different transportation system—find the unknown unknowns
  - Support structure must consider thermal expansion and contraction over delta T
  - Fuel weight decreases by factor of 2.8 LH2 versus Jet A
  - LH2 aircraft have lower lift to drag ratios, larger fuselages
  - Engine life and other technologies improves with LH2 cooling
- New aircraft configurations and technology are required to reduce fuel burn, weight to achieve net zero economically
- Liquid Hydrogen offers 50% reduction in emissions at substantially less risk than carbon SAF. Focus on 2,000-3,000 km range

Infrastructure / Power

- US Grid has 1,200 GW Capacity; Bottlenecks hamper growth
- 2,000 GW waiting installation approval (600 GW Storage)
- Wind, Solar, and Gas have all levelized to $30/MWh (2022)
- Its 10X cheaper to ship energy via pipeline than cables
- US Grid is a patchwork of 1000s of local utilities and does not account for the long-term benefits and lower costs
- Grid transmission based on fossil fuel must shift to decentralized microgrids to accommodate renewables and lower costs, but there is no functional system to figure out how to pay for and regulate the 1000s of utilities
- Wholesale PV combined with current electrolysis can produce hydrogen at $3/kg and likely lower when combined with wind and off grid power

Carbon SAF

- Carbon based Alternative Aviation fuel faces resource limitations, significant energy usage/capital to reduce emissions economically – 2050 goals are unsustainable

Reducing (Aircraft) Climate Impact Economically is a Massive Prize

IPCC: Human influence on the climate system is now an established fact

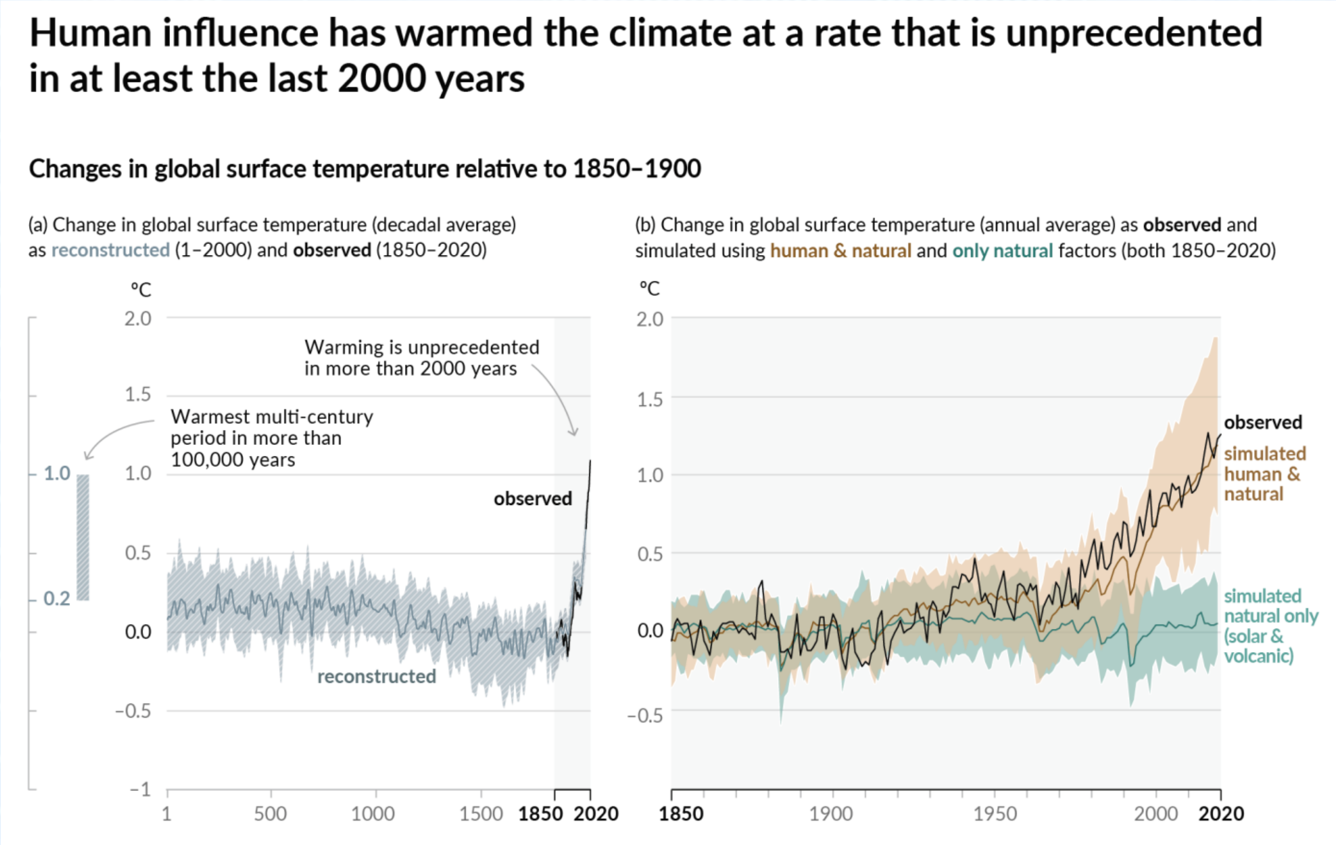
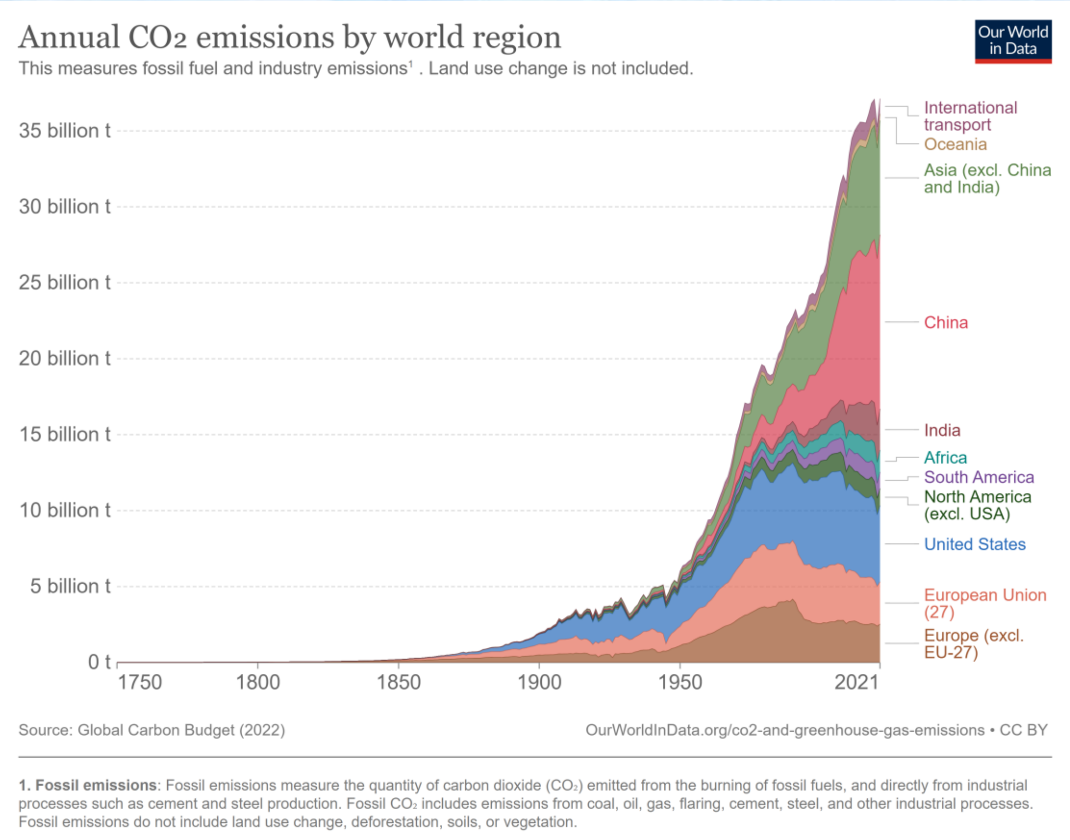


Figure SPM.1 in IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY,USA, pp. 3–32, doi: 10.1017/9781009157896.001 .]



CO_2, Greenhouse Gas Emissions - Our World in Data

Climate Change: Global Temperature

Understanding the future: A model anchored to many types of data with as long of timeframe as possible

Projected CO2 and temperatures are similar to only those from many millions of years ago

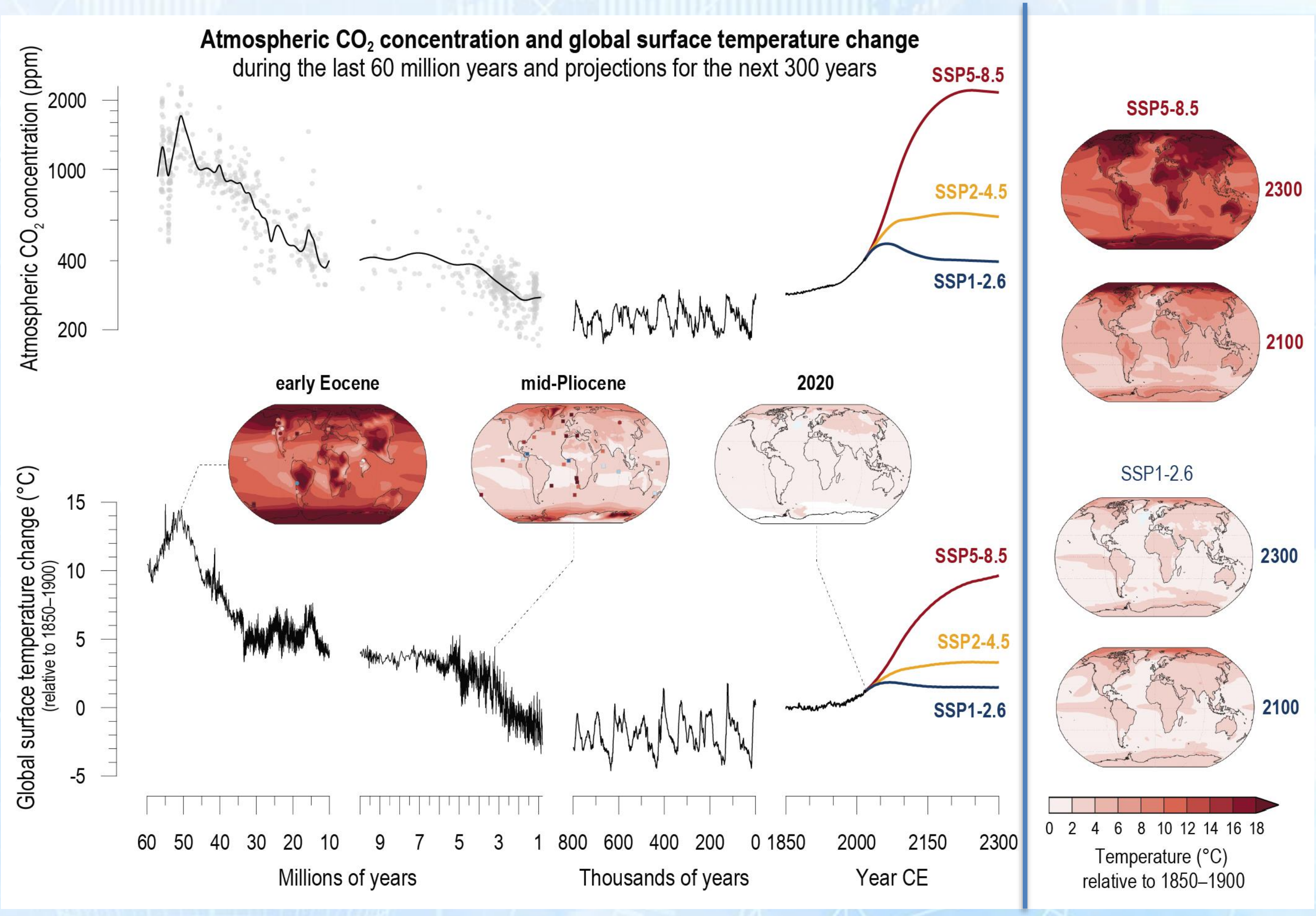
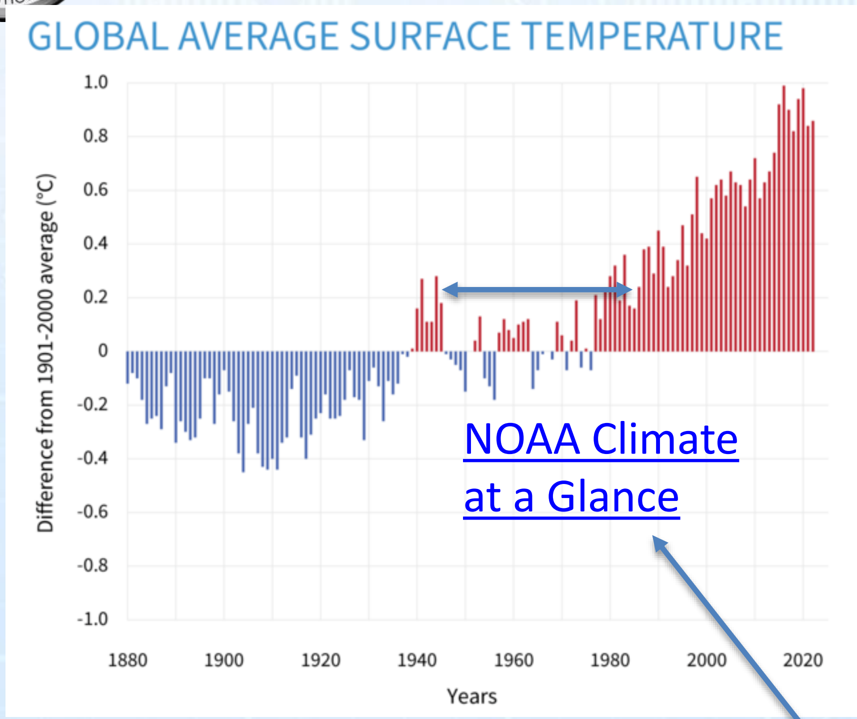


Figure TS.1 in IPCC, 2021: Technical Summary. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Chen, D., M. Rojas, B.H. Samset, K. Cobb, A. Diongue Niang, P. Edwards, S. Emori, S.H. Faria, E. Hawkins, P. Hope, P. Huybrechts, M. Meinshausen, S.K. Mustafa, G.-K. Plattner, and A.-M. Tréguier, 2021: Framing, Context, and Methods. InClimate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 147–286, doi:10.1017/9781009157896.003.]*

But the present rate of increase in carbon dioxide is unprecedented.
Past ice ages were very different from today

GDP, Emissions, Analyzing the Data



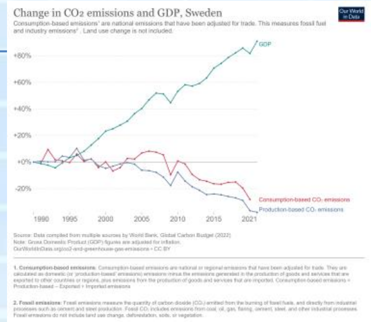
[NOAA Climate at a Glance]

Berkeley Earth Temperature Averaging Process

IPCC – Understanding 1.5C

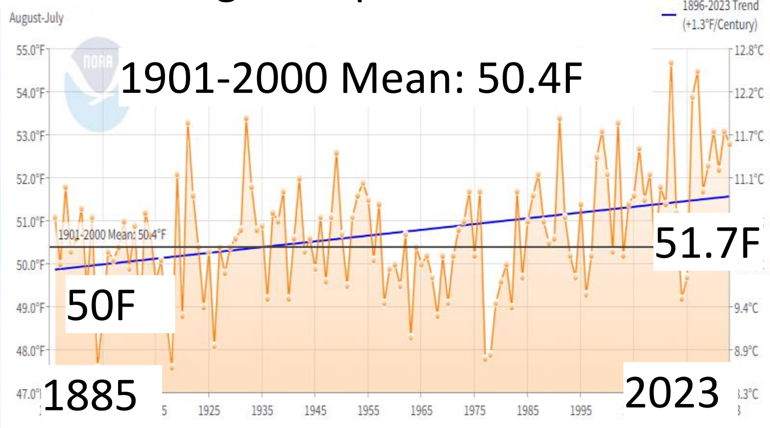
Look at all the data – understand mid-century cooling likely due to aerosols

Reuse freely- cite provided
CO₂ and Greenhouse Gas Emissions Our World in Data



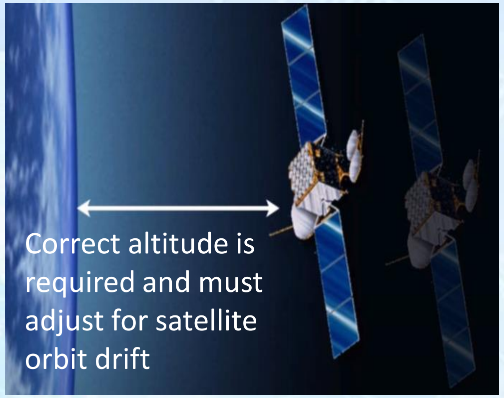
GDP vs Emissions by Country

Ohio Average Temperature



Despite their best attempts, scientists have been unable to explain how natural events have increased Earth's temperatures

Many individuals do not realize that for many years, Christie and Spencer claimed lower atmosphere was cooling-data was not being correctly interpreted. Their model *literally had wrong sign adjusting for the effects of satellite orbit drift*. Nighttime temperatures were warmer than the day-wrong physics.

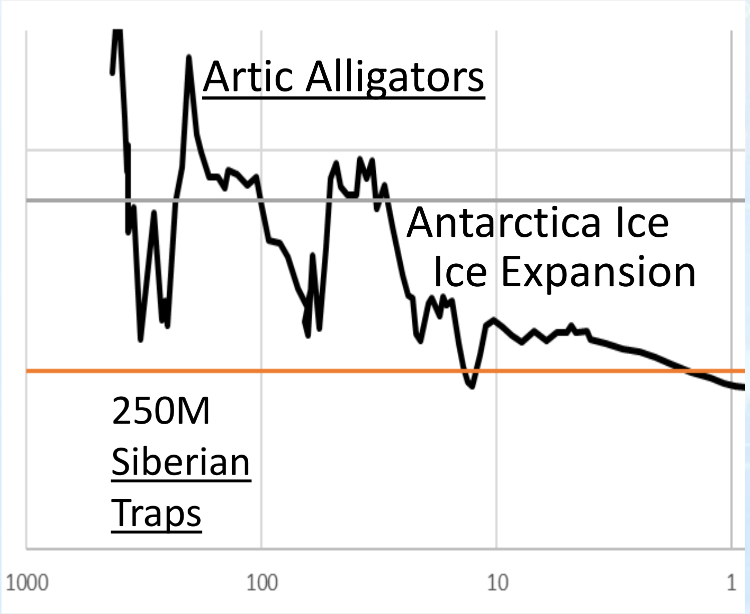


Large differences in tropical TMT trends are attributed to differences in the treatment of the *NOAA-9* target factor and the diurnal cycle correction.

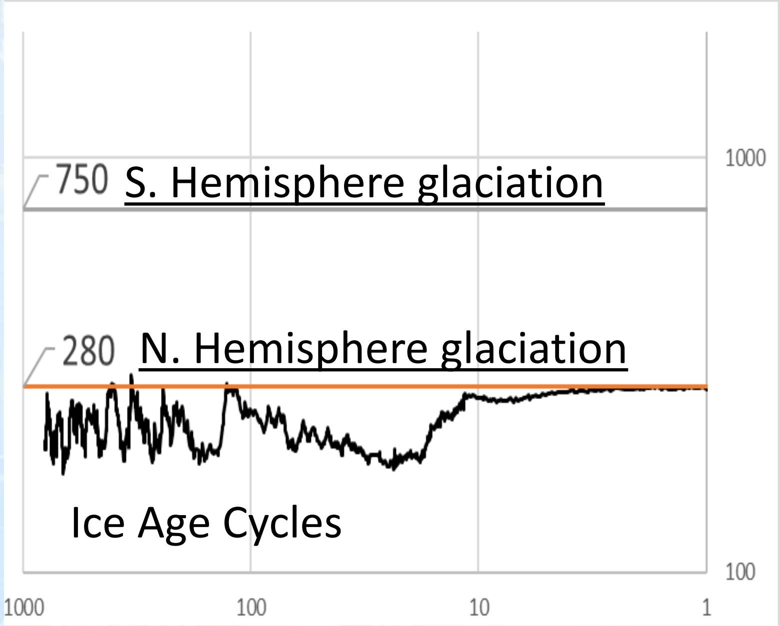
Earth's Atmospheric Carbon Dioxide History

- *Illustration only* Data: NOAA, Climate.gov
- Causes of Climate Change

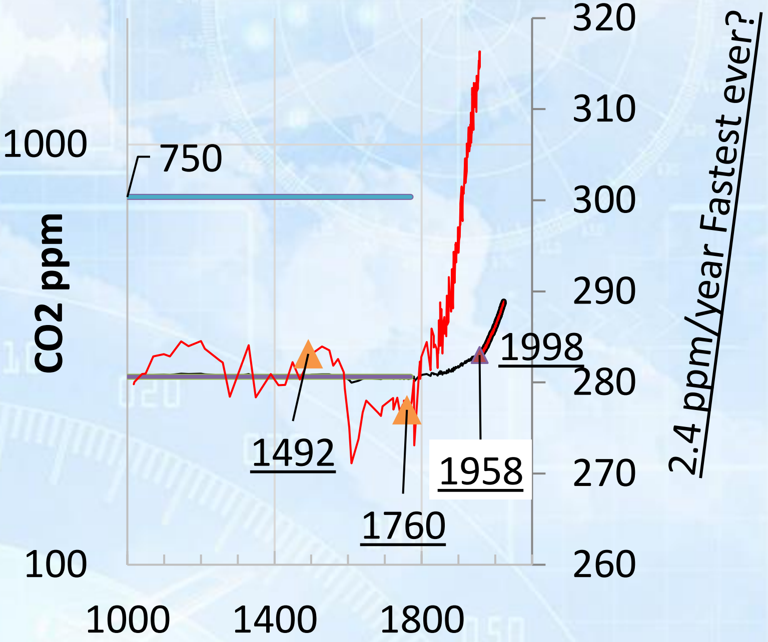
Same Data, Two Different Scales



Millions of Years Ago



Thousands of Years ago



252M Permian
80% Extinct
201M Triassic
30% Extinct

66M
Asteroid
tsunami
~~Dinosaurs~~

2M Volcano
Yellowstone
2.5M Human
Ancestors

650K Volcano
Yellowstone

What Will Earth Look Like When These 6 Tipping Points Hit?

What is the 'fly in the ointment' In Milankovitch theory of insolation?

Why 1.5C? -Vox

1492 1760 1958 1998

***~2 ppm per year** increase over past 60 years **is 100 times faster than natural causes** such as those that occurred at the end of the last Ice Age 11,000 to 17,000 years ago*

2020s Hydrogen Aircraft Development

56% 3450 mi, 3000 km

42% 2300 mi, 2000 km

56% of emissions less than 3000 km
42% of emission less than 2000 km

2020s – Hydrogen Development Efforts Focused on Regional and Short Range

- **France's ZEDC team produced Airbus' first-ever cryogenic tank in just over a year**
- May 2023 ArianeGroup conditioning system to warm LH2 for combustion proof-of-concept
- **Nov 2022 Rolls-Royce tests H2-powered engine**
- Airbus modify existing GE engine A380 demo
- June 2023 Airbus **H2 Fuel Cells APU ~ 5% energy**

- July 2023 ZeroAvia July 2023 – Protype Testing
  - H2 fuel cells power motors to turn propellers
  - **Retrofitted 19 Seat Dornier 228 aircraft, other engine kerosene- dual fuel**
  - 40-80 PAX region turboprop by 2027
- Universal Hydrogen Convert De Havilland Canada Dash 8-300 to fly on hydrogen and has other concepts

A fuel cell retrofit aircraft of 400 km to 700 km can reduce carbon intensity 88% vs Jet A and 35% versus e-kerosine

Dual Hydrogen-Jet Fuel Aircraft

Tackle easy part of the range sooner more economically

- **50% emission reduction if aircraft have 2080km of net-zero range**
- Lower and more stable fuel costs than SAF and Jet kerosene
- Lower maintenance costs
- Reduced noise and air pollution
- Auxiliary Power only ~5% of energy
- Boost Range for electric VTOL
- Hydrogen aircraft - #1 priority
- Challenge the Nation, World

  - *Adding LH2 tank reduces total footprint and emissions per revenue passenger km of entire dual fuel fleet*
  - *Adding LH2 tank provides early, gradual transition to work challenges, details and economics of a radically different transportation system*

Dual Hydrogen-Jet Fuel Aircraft Summary

- *1956* ***Dual Hydrogen Jet Fuel*** *Flight over Lake Erie; Limited 2020s LH2 Demonstrations*
- **Range drives emission strategy-50% less emissions with 2080 km range of net zero energy**
  - ***Lower and more stable fuel costs than SAF and Jet Fuel,*** *boost range for vertical takeoff*
  - ***Provides pull for H2 economy in fixed locations***
- ***Demonstrations are required today*** to address the requirement for well-insulated, sealed, cryogenic tank and fuel system and infrastructure challenges
- *Liquid hydrogen cooling enables fuel burn reductions, EP new aircraft configurations*
- *Alternative Aviation Fuel is driven by limited resources and is currently unsustainable. $3.5B hydrogen hubs and $1.25/gal US subsidy may change outlook*
- *Studies and demonstrations are required to develop a cost-effective, energy transmission and H_2 pipeline grids that can take advantage of hourly excess renewable energy*
  - *Studies are required to identify airports that can most readily adapt to LH2 aircraft*
  - *H2 hubs will require off-grid power near offshore wind and transportation, near steel, concrete, mining, others for high quality waste heat efficiency gain (15%); utilize liquefaction low quality waste heat*
- ***With 43,000 new aircraft by 2042, wait 30 years or <u>A new moonshot?</u>***